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ON THE ZEOLITES AND ASSOCIATED MINERALS FROM THE TERTIARY LAVAS AROUND BEN MORE, MULL.

BY

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D. Sc. 1915

[Plates I–III.]

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I.—**On the Zeolites and Associated Minerals from the Tertiary Lavas around Ben More, Mull.** By **W. F. P. M'Lintock**, B.Sc., Royal Scottish Museum, Edinburgh. *Communicated by* J. S. Flett, D.Sc., LL.D., F.R.S.

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[Plates I–III.]

Introduction.

The special features of interest attaching to the Tertiary igneous rocks of Mull have been made known to geologists mainly through the classic descriptions of Professor J. W. Judd and Sir Archibald Geikie. The point of view of these two investigators is, however, essentially geological, and they refer but little to the occurrence of minerals and rarely give precise localities. It is clear, too, that the late Professor M. F. Heddle did not make an exhaustive examination of many localities in Mull, for his collection in the Royal Scottish Museum contains very few specimens from that island. With a view to filling up this gap I have paid several visits to Mull, and this paper deals with some of the material which I collected. The officers of the Geological Survey who are at present mapping the island have helped me considerably with information and material; and to Mr J. E. Richey, B.A., who has surveyed the area from which a large part of the material was obtained, I am particularly indebted for assistance in collecting specimens from somewhat inaccessible localities.

The rocks around Ben More exhibit several peculiar characters which have been noted by Sir Archibald Geikie,* and also by Professor Judd,† who gives a description of their petrographical characters and altered state, and notes the presence in them of veins and nests of green and pink epidote. Again, Mr James Currie has recorded‡

* Sir Archibald Geikie, *The Ancient Volcanoes of Great Britain*, 1897, vol. ii, pp. 184, 213.

† J. W. Judd, "On the Propylites of the Western Isles of Scotland," *Quart. Journ. Geol. Soc.*, 1890, vol. xlvi, pp. 368, 369.

‡ James Currie, "The Minerals of the Tertiary Eruptive Rocks of Ben More, Mull," *Trans. Edin. Geol. Soc.*, 1898, vol. vii, p. 223.

scolecite, epidote, heulandite, stilbite, prehnite, etc., from Maol nan Damh, a spur of Ben More running down to Loch Scridain. Mr CURRIE remarks upon the peculiar assemblage of lime-bearing minerals in the cavities of the lavas and the absence of soda-bearing ones; but, as I shall show later, albite is quite a common associated mineral at this locality and at many others in the vicinity.

Apart from the points of interest already indicated, there is the further one that the lavas have been pierced by intrusive masses, and, as noted by Sir ARCHIBALD GEIKIE, have suffered in consequence considerable alteration—an alteration which is particularly prominent in the somewhat unstable minerals of the vesicles. In making a traverse of the country around Ben More one is forcibly impressed by the fact that for considerable distances around the plutonic centre the lavas differ entirely in character from those of the plateau-country far removed from the zone of intrusive rocks.* One of the most striking differences lies in the abundance of epidote in the cavities and veins of the central lavas, and its absence or extreme rarity in the basalts of the plateau. The central lavas, again, never show the spheroidal weathering to a brown loam so characteristic of the plateau-basalts, whilst there is the further difference, referred to by Mr CURRIE,† that the mineral association in the cavities is entirely different from that found in the normal lavas of the plateau. Different interpretations have been placed on these facts by Professor JUDD and Sir ARCHIBALD GEIKIE.

In the memoir already cited, the former observer groups the central lavas under the name of propylites, and he regards them as andesites of various types altered by solfataric action which "accompanied the intrusion of the acid masses."‡ This action was widespread, and he distinguishes it from the contact metamorphism locally induced in the rocks lying near the margins of the intrusions. As regards the date of the solfataric changes in the lavas, it is stated that in many places they have preceded the action of contact metamorphism, and in others the opposite may have taken place.§

Sir ARCHIBALD GEIKIE, on the other hand, sees in the propylites merely the representatives of the plateau-basalts altered by contact metamorphism,‖ and he states that he was unable to find any trace of the solfataric action described by JUDD. The point is of considerable geological significance, for upon it rest questions of interpretation of a complicated series of igneous rocks.¶

It occurred to me that an examination of the minerals in the cavities of the lavas might throw some light on the question of the cause and date of the alteration of the rocks, and in the present communication I shall deal with a very well-defined zone of zeolite-bearing lavas which can be traced from areas free from contact metamorphism almost up to the margin of one of the large acid intrusions. This

* Sir ARCHIBALD GEIKIE, *loc. cit.*, p. 388.

† JAMES CURRIE, *loc. cit.*, p. 226.

‡ J. W. JUDD, *loc. cit.*, p. 382.

§ J. W. JUDD, *loc. cit.*, p. 367.

‖ Sir A. GEIKIE, *loc. cit.*, p. 185 (footnote), p. 388 (footnote).

¶ J. W. JUDD, *loc. cit.*, p. 353.

zone occurs on An Gearna and Beinn Fhada, two ridges running from Ben More in a north-westerly direction, and also on Maol nan Damh, a spur running south-west from Ben More towards Loch Scridain. Its distribution is indicated on the accompanying sketch-map (fig. 1), and, as the geology of the region is complex, I include here short descriptions of the localities, kindly furnished by Mr Richey, who surveyed An Gearna and Beinn Fhada, and Mr Anderson, who mapped Maol nan Damh :—

"The parallel ridges of Beinn Fhada and An Gearna are situated at the western

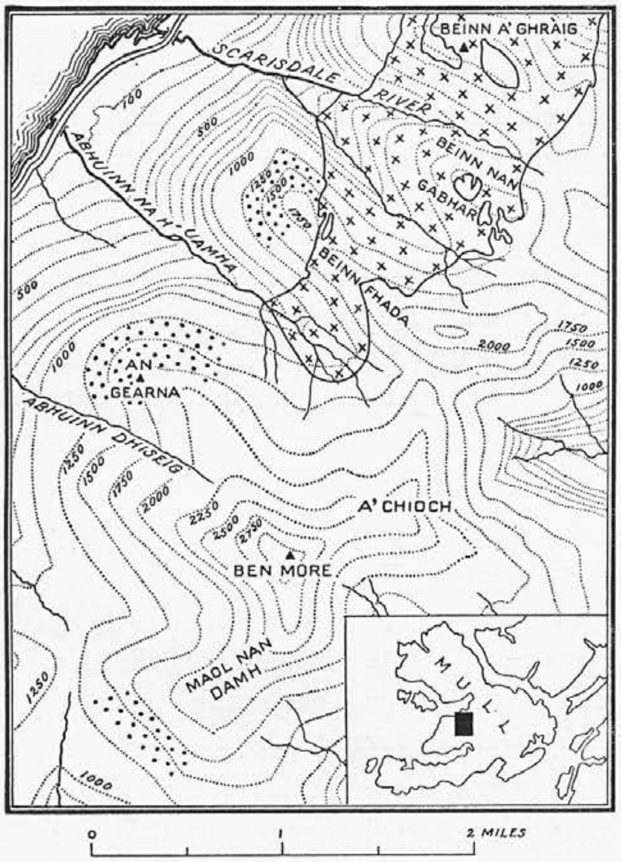


Fig. 1.—Map showing the distribution of the zeolite-bearing zone (dotted) and the granophyre (crossed).

border of the Mull plutonic centre. Tertiary plateau lavas form the country rock which is intruded by plutonics, sheets and dykes. The lavas are olivine basalts making thick cappings to the hills. A large granophyre mass (the Beinn a' Ghraig granophyre) cuts through Beinn Fhada and ends in the valley below, not reaching to An Gearna. Its junctions with the lavas, seen *in extenso* on the hill-face, slope steeply outwards, while the valley stream-sections show a like relation in detail. On the south-east end of Beinn Fhada part of an earlier granophyre is cut off against the granophyre of Beinn a' Ghraig.

"There are two series of sheets both intermediate between the granophyres in age. The belt of thin inclined sheets which encircles the Mull plutonic centre crosses

Beinn Fhada and cuts another series of thin basaltic sheets with a general westerly dip which are distributed throughout the district. Still earlier sheet-like masses of coarse dolerite form small scattered patches, of which some at least are later than the early granophyre.

"Some north-westerly dykes are earlier than the Beinn a' Ghraig granophyre, but the greater number of dykes belong no doubt to the north-west series proper and are the latest intrusions."

"The shoulder of Ben More known as Maol nan Damh is composed in the main of flat or very gently inclined lavas. Those forming the lower slopes of the hill are more basic, but the difference in character is not very marked and they are rather difficult to separate from the overlying flows, although the former are mapped as basalts and the latter as andesites.* The screes which flank the western slopes are in the lower more basic lavas.

"The largest intrusive mass is a flat sill of mugearite some 200 or 300 feet in thickness. This comes some 500 feet above the screes referred to. There are also a large number of minor intrusions, including porphyritic and non-porphyritic dolerite, and one or two that are more acid in character. As a whole, however, they are not so numerous as those which intersect the lavas in the higher portion of Ben More."

The Minerals of An Gearna.

One of the most convenient places for studying the mineralogy of the lavas is the ridge of An Gearna referred to above. On the north-eastern slope at a height of about 1200 feet, large amygdales, filled chiefly with a white fibrous zeolite, make their appearance in the screes and become plentiful at heights of 1300–1500 feet. The size of these amygdales is phenomenal, measuring, as they do, as much as 15 cm. × 10 cm. It is noteworthy that the lavas of the upper part of the hill alone yield the zeolite-filled vesicles; the amygdales in the lower lavas are small and are filled mostly with compact, massive albite. The fibrous zeolite is *scolecite*, and associated with it are *epidote*, *prehnite*, *garnet*, *albite*, and, much more rarely, *hornblende*, *calcite*, *chabazite*, and *thomsonite*.

Scolecite has usually been considered one of the rarer Scottish zeolites,† but on An Gearna it occurs in profusion, whilst it is also common on Beinn Fhada and Maol nan Damh; on Coire Bheinn, a hill lying two miles south-west of An Gearna, it is much rarer, although good specimens have also been got from there. It occurs in white fibrous aggregates and crystals, which in some cases reach a length of 10 cm., but, although many cavities have been broken open, no terminated crystal has been observed. In some cases when an amygdale is broken across, the scolecite shows a series of perfectly sharp rectilinear cracks or veins with perfectly flat, lustrous

* Microscopic examination has since shown that the lavas provisionally mapped as andesites are olivine basalts much like the underlying flows.

† *Cf.* J. G. Goodchild, "Natural History of Scottish Zeolites," *Trans. Glas. Geol. Soc.*, 1903, vol. xii, suppt., p. 62.

walls which, when examined closely with a lens, show a fine set of striæ formed by two sets of lines intersecting at about 60°. There can be little doubt that these cracks were once filled with calcite, which has left its cleavage traces on the adjacent scolecite. The following analysis was made by Mr E. G. RADLEY in the laboratory of the Geological Survey :—

		Calculated for Formula $CaAl_2Si_3O_{10} + 3H_2O$.
SiO_2	46·10 per cent.	45·9
Al_2O_3	25·05 ,,	26·0
Fe_2O_3	·55 ,,	...
CaO	14·17 ,,	14·3
MgO	·32 ,,	...
K_2O	·03 ,,	...
Na_2O	trace	...
H_2O at 105° C.	·13 per cent.	...
H_2O above 105° C.	13·78 ,,	13·8
	100·13 per cent.	100·0

The mineral is thus a typical scolecite practically free from alkalies.

The junction of the zeolite with the walls of the vesicle presents some interesting and unusual features. In place of the layer of green earth so frequently found underlying the Scottish zeolites, there is often a confusedly crystalline layer of yellowish-green epidote which sends off small radiating groups of spear-like crystals into the scolecite. In addition to epidote there are also sometimes present in this layer prehnite, garnet, albite, hornblende, and chlorite.

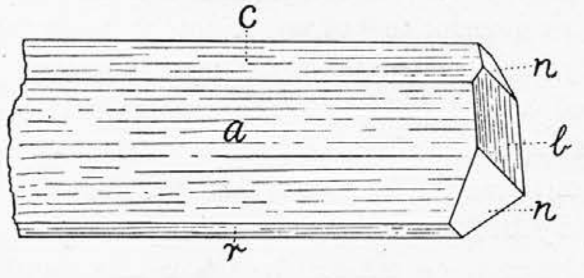


FIG. 2.—Crystal of epidote from An Gearna, Mull.

Epidote occurs invariably, however, in more or less abundance, and ranges in colour from blackish-green, which is rather rare at this locality, through various shades of yellowish-green to pale pink or almost colourless. It occurs in radiate groups of crystals which sometimes show the combination $a(100)$, $c(001)$, $r(\bar{1}01)$, $b(010)$, $n(\bar{1}11)$ (fig. 2). Besides occurring in intimate association with scolecite, epidote is also found in cavities where that mineral is absent. For example, at the north end of An Gearna, on the west slope near the summit, there is a pale, greenish-gray lava the vesicles of which are lined with a beautiful pink epidote on the top of which is usually a layer of colourless, botryoidal prehnite. The epidote occurs in groups of divergent crystals which are sometimes green at the one end and grade off into pink at the other; it frequently rests upon a layer of albite.

The following analysis, made by Mr RADLEY, shows this variety to be a lime-epidote, poor in iron, and owing its colour, doubtless, to the small amount of manganese present:—

		Molecular Ratios.		
SiO_2	38·69	·6405	·6420	6·00
TiO_2	·12	·0015		
Al_2O_3	28·54	·2793	·3228	3·01
Fe_2O_3	6·97	·0435		
FeO	·22	·0030	·4437	4·05
MnO	·29	·0040		
(CoNi)O	nt. fd.	...		
CaO	23·78	·4246		
MgO	·49	·0121		
K_2O	·03	...	...	...
Na_2O	trace	...	...	...
Li_2O	trace	...	...	...
H_2O at 105° C. . . .	·09	...	...	...
H_2O above 105° C. . .	·99	·055	·055	·514
	100·21			

The above analysis gives the formula $Ca_4Al_6Si_6O_{25\frac{1}{2}}H_2O$, in which the alumina is partly replaced by ferric iron and the lime by ferrous iron. The mineral obviously belongs to the somewhat rare series of epidotes poor in ferric iron referred to by Dr H. H. THOMAS in his description * of an epidote from Inverness-shire; it is also peculiar in having only half the normal percentage of water. Owing to the fibrous and poorly crystallised nature of the material an accurate determination of the optical characters was impossible; but, by means of a solution of methylene iodide and benzene, the mean refractive index was found to be 1·720, which accords well with the values given by Dr THOMAS.

Prehnite is a fairly common mineral in the vesicles, and occurs in the usual botryoidal form; sometimes it forms a dense white massive layer which is occasionally spotted with little yellowish or reddish masses of garnet. Typically it occurs in globular growths underlying the scolecite and seated upon epidote or albite. It is most plentiful at the locality previously noted in connection with the pink epidote. There, the geodes found in the screes are usually dull and weathered on the surface, but when broken open show beautiful rosettes of epidote projecting into massive white prehnite. In cavities in the latter mineral there occurs occasionally a pale

* H. H. THOMAS, "On an Epidote from Inverness-shire," *Mineralogical Magazine*, vol. xiv, p. 109.

greenish clay-like substance which, when crushed and examined under the microscope, appears to consist of a mixture of prehnite and yellowish-brown isotropic chloritic material.

Garnet.—This mineral is an unusual associate of zeolites, but on An Gearna it is of fairly frequent occurrence. Its presence has already been noted by Professor JUDD,* who mentions it as occurring with epidote in the volcanic agglomerates of the Hebrides. Mr CURRIE, in the paper referred to above, notes its absence on Maol nan Damh, but there can be no doubt that JUDD in his description had in mind the locality under consideration, although the rocks in which I have detected the mineral show none of the characters of volcanic agglomerates. The garnet varies in colour from pale yellow, or colourless, to deep brown, a beautiful wine-yellow tint being

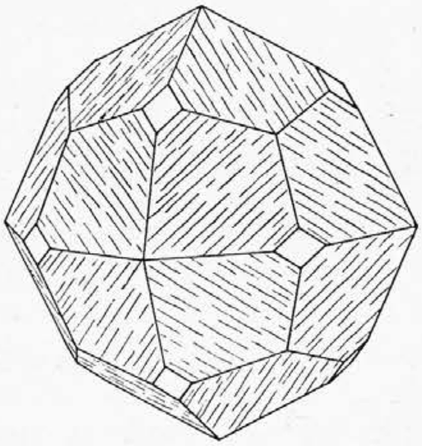


FIG. 3.—Crystal of garnet from An Gearna, Mull.

commonest. It occurs usually in crystals — occasionally ·5 cm. in diameter— studding the scolecite near the junction of that mineral with the underlying layer of epidote, prehnite, etc., although sometimes it is found well in the centre of the zeolite. The common form is the rhombic dodecahedron the faces of which are usually curved and irregular, but the form shown in fig. 3 has also been noted. In crystals of this shape it is of interest that the icositetrahedral faces show the unusual type of striation, parallel to the intersection of the icositetrahedron and the dodecahedron, noted by Professor SHAND † in his description of the garnets from Corsie Hill Quarry.

Besides occurring in direct association with scolecite, garnet has also been found with prehnite and albite, forming a layer between the two, and, rarely, imbedded in calcite. Much of the massive white prehnite found on the hill is spotted with garnet, and it is noteworthy that whenever the latter mineral occurs with scolecite, prehnite occurs in direct association with the two.

* J. W. JUDD, "On the Secondary Rocks of Scotland," *Quart. Journ. Geol. Soc.*, vol. xxx, 1874, p. 241.

† S. J. SHAND, *Proc. Perth. Soc. Nat. Sci.*, 1907, vol. iv, p. 210.

The following analysis was made by Mr RADLEY, and shows the mineral to be a typical lime-alumina garnet:—

SiO_2	37·66
TiO_2	·12
Al_2O_3	21·84
Fe_2O_3	4·07
FeO	·34
MnO	·53
(CoNi)O	nt. fd.
CaO	33·06
MgO	·45
K_2O	·75
Na_2O	1·17
Li_2O	nt. fd.
H_2O at 105° C.	nt. fd.
H_2O above 105° C.	·20
	100·19

Sp. g. = 3·61 at 7° C.

Albite is not infrequently found in the vesicles in association with the minerals already described. It rarely shows crystal form and occurs usually as a massive layer of variable thickness underlying scolecite or prehnite. When scolecite is present the layer of albite is separated from it by an irregular layer of epidote, whilst when prehnite overlies the felspar a zone of garnet occasionally separates the two. Vesicles also occur lined with albite upon which a layer of green epidote is seated, and albite-filled veins are of frequent occurrence in the lavas. The layer underlying the albite occasionally presents unusual features. In a few specimens it consists of white massive albite speared by long black fibrous crystals, measuring up to ·5 cm. in length and consisting of augite which, under the microscope, has the purple tint typical of the Tertiary basaltic lavas. These crystals occasionally wander into the albite of the vesicle proper, but the point will be more fully discussed when the microscopic characters of the vesicle-minerals come under consideration.

When crushed and examined under the microscope the albite is easily identified by the usual twinning, the symmetrical extinction angles on twin-lamellæ, and by its mean refractive index, which, tested in oil, is approximately 1·534; it is rarely clear and transparent, being usually filled with inclusions.

The lavas underlying the vesicular zone under consideration are much more compact and are characterised by much smaller amygdales which are filled with dense white or pink massive albite associated with epidote.

Calcite.—From the mineral association so far described, one might have expected calcite to be of frequent occurrence in the amygdales, but, as a matter of fact, it is rare and has been noted on few specimens. On one of these it occurs in a fairly large hollow in scolecite as a white, crystalline, much-cleaved mass, studded with yellow garnets. It lies near the walls of the vesicle and is separated from the scolecite by a space partially filled with yellow epidote. The surface of the scolecite adjoining this space is flat and shows the characters possessed by the walls of the rectilinear cracks already described as occurring in this mineral. Support is thus lent to the view that these cracks were once occupied by calcite, which has since been removed.

Chabazite and Thomsonite.—In addition to scolecite these are the only other zeolites which have been noted on An Gearna, and they are extremely rare. The former mineral has been found on only one specimen, where it occurs as simple rhombohedra lining a cavity in white, massive prehnite spotted with reddish-brown garnet; albite and epidote are also present. Thomsonite has been noted in sheaf-like growths intimately associated with prehnite, albite, and scolecite. It has also been found on the north-east slope of Beinn Fhada associated with albite and prehnite, and with like associates on Coire Bheinn.

Hornblende can be observed occasionally in hand-specimen as tufts or aggregates of acicular crystals always near the walls of the vesicle. It spears the scolecite and is intimately associated with epidote. As will be shown later, it is a common microscopic mineral in the amygdales.

The Minerals of Maol nan Damh.

To appreciate correctly the significance of the most unusual mineral association described above, it is necessary to study the occurrences on the neighbouring hills. In the paper already quoted, Mr Currie records the presence of scolecite, epidote, calcite, celadonite, heulandite, and, much more rarely, stilbite, and prehnite from the upper lavas of the south-western side of Maol nan Damh, a spur of Ben More running in a south-westerly direction towards Loch Scridain (see fig. 1). He very kindly presented specimens to the Royal Scottish Museum, and from an examination of them I came to the conclusion that what had been determined as heulandite was in reality albite. In the course of correspondence with me Mr Currie very frankly stated that he, too, was now of the same opinion, and from an examination of specimens collected by Mr E. M. Anderson and myself there can be no doubt that albite is of very frequent occurrence in the vesicular lavas at this locality.

The zeolite-filled cavities are if anything larger and more abundant than those of An Gearna, and it is clear that here we are dealing with a similar set of rocks. Scolecite, as described by Mr Currie, is by far the most abundant mineral, and associated with it are epidote, chlorite, albite, calcite, and, more rarely, prehnite. Heulandite and stilbite are exceedingly rare and have been noted on only one specimen, where they fill up the spaces between a crystalline aggregate of quartz, albite, and epidote, whilst chabazite has been noted in a vesicle filled with an aggregate of scolecite and prehnite. Cubes of pyrites have also been observed enclosed in massive prehnite.

One specimen of special interest shows a hollow vesicle lined with, apparently, dull, opaque icositetrahedra of analcite upon which are seated crystals of pale green epidote; the icositetrahedra when crushed and examined under the microscope are seen to consist of albite which has replaced the zeolite.

The typical vesicles filled with fibrous scolecite sometimes reach a phenomenal size, the largest one found measuring 15 cm. along its greatest length. They are usually closely packed with scolecite, terminated crystals of which are exceedingly rare: a few have been found, however, showing the combination $b(010)$, $m(110)$, $d(101)$, $o(111)$. In the simplest cases the scolecite is seated upon a layer of chlorite, but such specimens are rather exceptional. A more common association is (beginning from the wall of the amygdale) chlorite with deep green epidote, then a layer of crystalline albite, white or pale pink in colour, and of variable thickness, and, lastly, scolecite which fills the vesicle; a layer of prehnite sometimes intervenes between the scolecite and albite. Calcite occurs fairly frequently in crystalline, much-cleaved masses enclosed in the scolecite near the junction with the underlying minerals.

Epidote is exceedingly abundant. When it occurs with scolecite it is always found near the walls of the vesicle in intimate association with chlorite. It forms groups of dark green radiating crystals which sometimes spear the scolecite and are occasionally completely enclosed by it. In a second type of vesicle, where scolecite is absent, it occurs in groups of divergent crystals seated upon albite, whilst in a third type the amygdale is packed with massive chlorite, in the centre of which is a kernel of fibrous epidote.

Chlorite is universally present in the cavities and shows various interesting features, some of which have an important bearing on the question of the date of formation of the vesicle-minerals. It was obviously one of the first to be deposited, and forms a dark green, compact, and massive layer lining the walls of the amygdale. This layer varies considerably in thickness: in some cases, especially when the vesicle is small, it fills the cavity; in others it forms a thin and patchy priming for the overlying minerals, which may be scolecite, albite, epidote, or prehnite. In many cases the chlorite is quite homogeneous, but it often contains crystals and grains of deep green epidote, whilst in a few specimens acicular crystals of black augite, measuring up to ·4 cm. in length, can be detected. These crystals occur usually at or near the junction of the chlorite with the rock, but occasionally they are found well within the chlorite layer and even wandering into the overlying epidote, albite, and prehnite. Sometimes they are arranged radially to the walls of the vesicle to which they are often attached, but in many instances they lie tangentially to the boundary and have no visible point of attachment to the rock. On one specimen the layer of chlorite and augite can be seen to connect with a vein packed with similar material which pierces the lava. The crystals of augite in the centre of the vein are arranged roughly parallel to the walls. A few cavities have been found in which prehnite is specially abundant. The underlying layer consists of chlorite speared with acicular augite with which albite is intimately associated; in such cases the augite is occasionally found enclosed in the immediately overlying prehnite.

Owing to the dark colour of the chlorite and the frequent occurrence of fibrous epidote, it is difficult to detect these acicular augites in hand-specimen. They are best seen on the weathered surface of the chlorite, which is pale, and they can be readily identified by an examination of a little crushed material under the microscope, when the purple colour, cleavage, and positive optical sign distinguish the mineral at once from epidote. They are a prominent feature in sections cut through the junction of the rock with the vesicle, and their significance will be discussed when the origin of the zeolites comes to be considered.

In addition to vesicles, the lavas also carry veins filled with albite in which are, occasionally, clear crystals of quartz and rhombohedra of chabazite. Veins filled with albite, scolecite, and prehnite also occur, and there are other minerals which can only be detected under the microscope, and which will be described later.

Meanwhile it is interesting to compare the differences, obvious in hand-specimen, between the minerals of Maol nan Damh and those from An Gearna. First, we may note that the dark green chloritic layer underlying the zeolites is much sharper and better developed on Maol nan Damh than on An Gearna, where its place is usually taken by a confused zone of yellow epidote with which tufts of green hornblende are sometimes associated. The second notable difference lies in the colour of the epidote predominant at the two localities. At Maol nan Damh it is typically of a deep, bottle-green shade, whilst at An Gearna it is usually pale yellow, brown, or pink; the last variety has not been found at Maol nan Damh. A third difference lies in the abundance of garnet on An Gearna and its absence or extreme rarity at Maol nan Damh. On one or two specimens collected by myself I have noted very small crystals in microscopic section, whilst on another collected by Mr Anderson it is visible to the unaided eye; Mr Currie notes its absence in the material collected by him.

It is clear, therefore, that on An Gearna we are dealing with the somewhat metamorphosed representatives of the vesicle-minerals of Maol nan Damh, and it is interesting to trace this well-defined zone towards the large intrusive mass of granophyre which forms the centre of Beinn Fhada, a ridge running parallel to An Gearna at a distance to the north-west of about a mile.

The Minerals of Beinn Fhada.

On this hill the cavities are neither so plentiful nor so large as those obtained at the localities previously described, but good specimens can be obtained from the screes at the north-western extremity of the ridge at heights of 1200–1500 feet. There the vesicles are filled with scolecite underlain by a layer of pale green or yellow epidote intimately associated with garnet, prehnite, and, frequently, albite. The boundary of this layer with the zeolite is highly irregular, and every now and then it sends off growths into the scolecite, tufted aggregates of which can often be seen enclosed in the prehnite and epidote. On some of the specimens there is a white massive mineral which occasionally merges into opaque, white tufts of zeolite. When examined under the microscope the massive mineral proves to be prehnite, which is clearly replacing the scolecite originally in the vesicle. Beautiful specimens also occur in which the scolecite is sprinkled with groups of crystals of epidote and garnet, pale pink, yellow, or even red in colour.

A peculiar vesicular, pale gray lava has also been noted in which the vesicles present rather unusual features. They are lined with a thin layer of black chlorite, which is succeeded by epidote or stilbite, sometimes well crystallised, or by a massive aggregate of the two in which the epidote occurs as grains and crystals enclosed in the zeolite. When the stilbite is absent the epidote is abundant, and *vice versa.* Some of the vesicles, again, are lined with dull brown botryoidal material which, on examination, proves to be epidote coated with prehnite. A study of the vesicles in this rock strongly suggests that some of the epidote at least has been developed at the expense of the lime-bearing zeolite.

Thomsonite is occasionally found on this part of the hill. It is underlain by the usual zone of epidote and prehnite, spotted and veined, however, with albite.

Along the north-east slope of the hill the zeolites and, indeed, amygdales get much rarer as the junction of the granophyre with the lavas is approached, and, when found, they show unmistakable signs of having been baked and altered. At a point almost S.S.W. of the summit of Beinn a' Ghraig prehnite is of common occurrence in the vesicles and, occasionally, white fibrous masses are found which look like scolecite, but, on examination, prove to be prehnite, which is replacing it. On one or two specimens cleaved masses of white calcite occupy hollows in massive white prehnite, and at the junction of the two minerals there are exceedingly minute crystals of white, perfectly colourless garnet.

Still nearer the granophyre the original character of the amygdales is completely changed; the junction with the walls loses its sharpness, and the material filling the cavities seems to merge into the surrounding rock. Prehnite veined and riddled with a pale yellow epidote and garnet, pale yellow to almost black in colour, is very common, whilst in other cases the vesicle is filled with a pale pink massive material which consists largely of a mixture of garnet and epidote.

It is thus clear from the field evidence that the zeolites were formed before the intrusion of the granophyre and have been metamorphosed by it. Microscopic examination of a series of sections through the amygdales confirms this conclusion and reveals a number of interesting contact minerals not visible in hand-specimen. But, to understand correctly the course of the metamorphism, it is necessary to find out what were the original minerals in the vesicles, and, if possible, the date of their formation. Interesting light is thrown on these questions by a study of the microscopic characters of the amygdales of Maol nan Damh, which also shows the relationships of the minerals to each other and to the lava in which they occur.

The Origin and Relationships of the Vesicle-Minerals.

I. *Introduction.*

The question of the origin of the zeolites so frequently found filling the vesicles of lavas is one which has excited very great diversity of opinion. In modern works of reference on mineralogy they are usually classed as secondary minerals which owe their origin to the decomposition of the minerals of the lava at a date subsequent to its consolidation.* This view was strongly supported by the late Mr J. G. Goodchild, who expressed the opinion † that they were formed by the action of percolating surface waters upon the original minerals of the rock. He seems to have had doubts, however, about this explanation holding good for the occurrences under description, for he refers specially to the association in the centre of Mull as owing its origin perhaps to solfataric action. ‡ In this he no doubt was following Professor Judd, who expresses that view in the memoir already cited.

Dr A. Harker, in his description of the Tertiary igneous rocks of Skye, regards the zeolites as the products of the final phase of consolidation of the lavas, § and states that the subsequent changes produced by the action of percolating meteoric waters are of a different order and readily distinguishable from the process of zeolite-formation. This view has been strongly advocated by Mr James Strachan, ‖ who considers that zeolites, agates, green earths, etc., were formed during the last period of cooling of the lavas in which they occur. Similar explanations for certain occurrences of zeolites have been offered by Blumrich ¶ and Pelikan,** whilst Dr J. S. Flett,†† in his account of the teschenites of the Edinburgh district, states that some of the analcite in these rocks may be primary.

Directly bearing upon the question of the origin of zeolites are the occurrences in the syenite pegmatite veins of the Norwegian syenites ascribed by Brögger ‡‡ to

* *Cf.* Hintze, *Handbuch der Mineralogie*, vol. ii, p. 1658.

† J. G. Goodchild, "On the Genesis of Some Scottish Minerals," *Proc. Roy. Phys. Soc. Edin.*, 1899, vol. xiv, p. 190.

‡ *Loc. cit.*, p. 211.

§ A. Harker, *Mem. Geol. Surv.*, "The Tertiary Igneous Rocks of Skye," 1904, p. 45.

‖ James Strachan, "The Carnmoney Chalcedony, its Occurrence and Origin (with a General Note on the Formation of Secondary Siliceous Minerals in Volcanic Lavas)," *Proc. Belfast Nat. Field Club*, 1906, vol. ii, appendices vii and viii, p. 336.

¶ J. Blumrich, *Tschermak's Min. Pet. Mittheil.*, 1892, vol. xiii, p. 482.

** A. Pelikan, *ibid.*, 1906, vol. xxv, p. 113, and *Sitz-Ber. Wiener Akad.*, 1901, iii, p. 341.

†† *Mem. Geol. Surv.*, "The Neighbourhood of Edinburgh," 1910, p. 296.

‡‡ W. C. Brögger, *Zeitschrift für Krist. u. Min.*, 1890, vol. xvi, p. 168.

the action of magmatic solutions. C. N. FENNER * has given full descriptions of the mode of occurrence of zeolites and other minerals in the Watchung basalt, New Jersey. He shows how the minerals were deposited in a definite order from aqueous solutions and how the earlier anhydrous and slightly hydrous ones are succeeded and replaced by the later-formed, more hydrous compounds. He considers that the zeolites and their associates were deposited during the cooling of the basalt, but, from various facts connected with the occurrence, concludes that the water which caused the change was derived largely from the underlying sediments.†

II. *Petrography of the Vesicles.*

Confining ourselves for the present to the well-defined scolecite-bearing zone on Maol nan Damh, we find that, under the microscope, the rock proves to be a typical olivine basalt. Fresh olivine is absent, but chloritic pseudomorphs after it can be detected. The augite occurs in somewhat large sub-ophitic plates and is of the purple colour so common amongst the Tertiary basalts; it is frequently altered to chlorite, but much of it is quite fresh. The felspar, which occurs in small laths piercing the augite, contains veins and inclusions of chlorite and has been albitised. Owing to the abundance of inclusions it is often difficult to apply the Becke test to the laths; but whenever a determination could be made the refractive index was found to be below that of balsam, and the mineral appears in most cases to be albite or, at least, a very acid plagioclase. In the coarser portions of the basalt the albitisation is very pronounced, and sometimes—presumably when the original felspar was highly basic—crystals are now represented merely by a chlorite pseudomorph with or without an albite rim. This point has been observed in some of the rocks from Devonshire.‡ The peculiarity of albitisation is of general occurrence in the rocks around the plutonic centre in Mull, and, as epidote is also characteristically present, an interdependence of the two phenomena is suggested.

In addition to the above-mentioned minerals, black oxide of iron is also present in fair quantity in the basalt.

Sections cut through the junction of the rock with the amygdales show interesting features which not only reveal the order of events during the deposition of the vesicle-minerals, but also suggest that they were deposited during the cooling of the lava itself. The identification of the minerals is a comparatively simple matter, and, owing to the abundant development of the various species on the specimens selected, the determinations can usually be checked by an examination of the various powders in oils of suitable refractive index. In general the zeolites are

* C. N. FENNER, "The Watchung Basalt and the Paragenesis of its Zeolites and Other Secondary Minerals," *Ann. N.Y. Acad. Sci.*, 1910, vol. xx, pp. 93–187.

† *Loc. cit.*, p. 106.

‡ K. BUSZ, *Neues Jahrbuch für Mineralogie*, 1896, vol. i, p. 59; J. S. FLETT, *Mem. Geol. Surv.*, "The Geology of Newton Abbot," 1913, p. 60.

difficult to determine under the microscope, as in many cases they possess low refractive indices, weak double refraction, and anomalous optical characters which often make it impossible accurately to determine individual members by examination of thin sections alone. In the present case, however, the number of zeolites is limited and the individual species can be readily identified.

Scolecite occurs in long fibrous crystals (refractive index, 1·5) which are weakly birefringent, extinguish obliquely, and have the zone of elongation negative. Transverse sections across the fibres have very low birefringence, and in many cases show the emergence of an acute, negative bisectrix with a low axial angle. These characters distinguish it at once from thomsonite (and natrolite), which shows much stronger birefringence, straight extinction, and the emergence of an acute, positive bisectrix perpendicular to the direction of elongation. The axial angle is large; and the optic axial plane is perpendicular to the zone of elongation, which is consequently sometimes positive and sometimes negative: in the former case the section shows low birefringence and is perpendicular to the acute bisectrix. The only other zeolite observed in the slides is heulandite, and it is of rare occurrence. It shows good cleavage and can be always determined by the fact that cleavage flakes show the emergence of a positive, acute bisectrix.

The prehnite is characterised by good cleavage, high refraction and birefringence, straight extinction and positive optical character. It occurs in large, compact, colourless plates and spherules which usually show wavy extinction under crossed nicols. They are often built up of sectors which radiate from a point in the plate, and, on being rotated under crossed nicols, the section shows two dark hyperbolæ which close up and open out in directions at right angles to each other. Idiomorphic crystals with uniform extinction have not been found, but areas large enough to show the characteristic optical characters are quite common.

The determination of the epidote and the albite offers no special difficulty, as they are quite typical. The albite, however, is sometimes so turbid that it is difficult to identify it, and in such cases the mineral was always separated from the hand-specimen, powdered, and examined in oil of refractive index 1·534 under the microscope. No attempt was made to identify the different kinds of chlorite present. The mineral varies in colour from pale yellowish-green to deep green, the latter variety being distinctly pleochroic. It occurs usually in small, vermicular growths, but is also found in fibrous and platy forms.

With the help of the sections it is possible roughly to divide the vesicles into two main types:—

(*a*) Those vesicles whose junctions with the rock are sharp, and which do not contain any of the igneous minerals of the rock.

(*b*) Those vesicles whose junctions are not so sharp, and which contain, especially in their outermost zones, igneous minerals similar to those found in the rock.

(*a*) This type of vesicle tends to be common in the more finely grained portions of the lava, and, with exceptions, the larger specimens conform to it. In the simplest cases the amygdale is lined with a layer of chlorite containing an occasional lath of albite and succeeded by scolecite which is crowded with inclusions of chlorite for some distance from its highly irregular junction with that mineral [73].*

In the more complex types spherules of prehnite enclosing chlorite and, occasionally, minute greenish fibres, which may be augite, occur sporadically on the walls of the amygdale. They are succeeded by a zone of chlorite, enclosing crystals of turbid albite and an occasional irregular grain of yellow epidote, and this, in turn, gives way to a layer of cloudy albite; the rest of the amygdale is packed with scolecite into which some of the albite occasionally wanders [74].

The spherules of prehnite are roughly hemispherical in shape, and under crossed nicols the black bar travels round the section when it is rotated. Not infrequently the extinction direction is continued into the rock so as roughly to complete the circle, and close examination shows that the albite laths of the rock in the complementary hemispherical area are replaced by prehnite which is optically continuous with the prehnite of the amygdale. Under high powers minute crystals of purple augite can be seen projecting into the spherules of the vesicles and converted at their tips to a green mineral which may be pyroxene or amphibole. The replacement of albite by prehnite is also shown by the fact that occasionally the spherules contain small rectangular turbid areas exactly similar in appearance to the albite laths, but which now consist of prehnite [113].

The same relationship of scolecite to albite is also exhibited. The junction between the two minerals is highly irregular, and the scolecite frequently contains corroded crystals of albite which it is clearly replacing. The further the albite is removed from the junction the more it is corroded, until finally it is entirely replaced by scolecite, the only trace left of it being a turbid patch corresponding in outline to the original lath.

When epidote occurs it is always greenish-yellow in colour and shows the usual pleochroism. It is found chiefly in the outer zone of the amygdale, and is frequently studded with inclusions of chlorite. Occasionally it encloses sharp, idiomorphic crystals of albite somewhat clearer than usual [71], and its junctions with that mineral are often quite sharp and well defined, although sometimes the albite exhibits outlines suggestive of corrosion [63].

The relationships of prehnite and scolecite to epidote offer some interesting features. In the case of prehnite one finds that the junctions between it and the epidote are not infrequently sharp, but often there are traces of corrosion of the epidote crystal. Particularly is this the case when the epidote is enclosed in the centre of the prehnite spherules, where it often occurs as a patch showing irregular and corroded junctions with numerous minute fibres projecting into the prehnite.

* The numbers refer to a collection of slides in the Royal Scottish Museum.

When the epidote is bounded by scolecite, this peculiarity is even better shown. Large crystals of epidote end against the zeolite in a series of fibrous tufts, whilst the outline of the crystal is frequently interrupted by little rectangular patches filled with clear scolecite; occasionally a large crystal has been dissected into a number of separate fragments which extinguish simultaneously under crossed nicols [113].

The junction of the prehnite with the scolecite is never a sharp one. The spherules of prehnite are separated from the zeolite by a band of fibrous, crystalline prehnite, which terminates against the scolecite in a highly irregular manner. Irregular patches of prehnite are also found well within the scolecite layer.

The minerals in these vesicles were thus deposited in the following order:—(1) albite, (2) chlorite, (3) epidote, (4) prehnite, (5) scolecite, and there is distinct evidence that with changing conditions some of the material formed in the first stages has been partly replaced by later-formed minerals.

A marked feature in some of the slides is that the rock for some distance around the vesicle is very much altered and shows a large development of chlorite and black oxide of iron. This altered zone is sometimes vesicular, the vesicles being filled with epidote or chlorite, or a mixture of the two [67], and it grades off into the normal basalt.

(*b*) This type of vesicle is best developed in the coarser basalt, and is usually characterised by a considerable amount of prehnite, although there is a good deal of variety in the way in which the minerals occur. In the simplest cases small cavities are filled with prehnite, which encloses prismatic crystals of purple augite, fresh and unweathered and similar in all respects, except habit, to the ophitic augite of the surrounding rock. Frequently they are clearly attached to the walls of the amygdale, but occasionally they are surrounded on all sides by prehnite and occur well in the centre of the vesicle. The mode of occurrence of these crystals and their difference in habit from the augite of the rock show clearly that the vesicles were the seat of igneous crystallisation after they had been formed [107].

Some of the larger vesicles show similar crystals round their junctions with the rock. When chlorite forms the first zone of the amygdale, the long prismatic augites project into it and are sometimes completely surrounded by it. Their boundaries are clear and sharp, although occasionally there is evidence of corrosion and alteration to hornblende and chlorite; but, generally, their fresh and unaltered condition contrasts rather forcibly with the decomposed state of much of the augite of the rock. The chlorite, which sometimes forms a layer of considerable thickness, may be succeeded by a confused zone of chlorite, albite, and yellowish-green epidote with a few patches of muddy scolecite. Upon this is seated a layer of turbid albite, and scolecite fills the central portion of the vesicle. Prehnite may be present as small spherules occurring here and there around the walls; it usually contains a fair amount of chlorite, and is frequently pierced by the large crystals of augite [65].

In another type of vesicle the wall is lined with a more or less well-developed layer consisting of large acicular purple augites with idiomorphic laths of albite which sometimes pierce the augite. This layer may be succeeded immediately by scolecite intermingled with chlorite, which grades into a well-defined zone of chlorite upon which is seated scolecite, enclosing crystals of yellowish-green epidote. The purple augite usually projects from the augite-albite layer, but occasionally crystals are found surrounded by scolecite and at some distance from the walls of the vesicle; a large projecting crystal has been noted in which a transverse fracture has been filled with scolecite. This augite is often quite fresh and unaltered, but sometimes it has been partially converted to green fibrous hornblende or yellow epidote similar to that found in the amygdales; crystals have been noted of which the one half is purple augite, and the other, yellow epidote. The laths of albite are full of inclusions, and they, too, wander into the overlying scolecite [70].

The augite-albite layer is usually thin and patchy, but specimens occur in which it reaches a thickness of 1 cm. When it is well developed, chlorite is abundant in it and fills up the spaces between the large augite crystals which it frequently encloses. Sections across this layer show it to consist of crystals of purple augite, long skeletal crystals of magnetite, with albite, chlorite, and apatite. The augite is idiomorphic and has sharp junctions with the chlorite, although here and there it shows signs of corrosion and marginal alteration to chlorite and hornblende. When the long prismatic crystals are attached to the walls they project radially into the vesicle, but when they occur well within the layer they lie often with their long axes parallel to the walls. This layer may be succeeded by a zone of chlorite and epidote, the latter mineral showing the usual irregular junctions and full of chlorite inclusions; a layer of turbid albite is the next deposit, then a layer of prehnite, and finally scolecite [23]. The prehnite in some cases is obviously replacing the turbid albite, for not only does it contain phantom crystals of that mineral but occasionally it occurs as veins cutting across the felspar, crystals of which are optically continuous on opposite sides of the vein. Some of the smaller amygdales show this phenomenon even better. The first layer is a well-defined zone of pegmatitic augite, albite, and chlorite, the augite showing the usual features of corrosion and, occasionally, occurring as detached crystals well towards the centre of the vesicle. This layer is succeeded by prehnite, more or less turbid and enclosing thoroughly corroded patches and phantom crystals of albite as well as a little chlorite. Scolecite comes next; it, too, contains corroded albite and also patches of prehnite with little phantom albites near their centres [111].

Besides being highly vesicular, the lavas are sometimes traversed by white veins showing at their junction with the rock a very well-developed pegmatitic layer of augite, albite, and chlorite. Under the microscope this layer shows the features already described: namely, the long prismatic augites, often roughly parallel to the walls, the turbid albite, the magnetite, and the chlorite. Upon it is deposited a layer of turbid albite with some prehnite and small nests of scolecite. The latter mineral is clear and transparent and contains crystals of epidote, showing distinct signs of corrosion, and also fibres and crystals of pale green slightly pleochroic augite [109]. These veins resemble in some respects the contemporaneous veins described by Dr J. S. Flett * as occurring in the teschenite of the Barnton railway cutting, Midlothian.

A few exceptional vesicles have also been noted. Mention has already been made of one lined with albite pseudomorphous after analcite. Under the microscope the pegmatitic layer of augite, albite, magnetite, and chlorite is seen to be well developed and is succeeded by the albite-pseudomorphs. A smaller vesicle underlies the main one and is filled with albite secondary after analcite, chlorite moulded upon the pseudomorphs and purple augite which occurs in large crystals lying around the walls or stretching across the vesicle and projecting into the larger amygdale through a canal which connects the two. The mode of occurrence of albite in this amygdale points to an increase in temperature which may have been caused by local circumstances during the period of vesicle-infilling or by the injection of some intrusion long after the zeolite was formed. The absence of any other sign of metamorphism in the rock points to the former explanation being the probable one.

Another specimen shows a fairly large vesicle filled with chlorite throughout which are scattered a number of white spots. In thin section the rock is a typical basalt showing the usual features, but the first mineral to be deposited in the amygdale was garnet. It occurs as a pale brown layer of variable thickness and exhibits signs of corrosion on its inner margin where it is overlain by scolecite or chlorite. In places signs of an hexagonal outline are visible in some of the grains lying away from the layer, but they are always corroded and tend to be circular. The further the grains are removed from the walls the more do they show signs of replacement, and in one or two instances they are represented by spots which are doubly refracting and which merge into the surrounding zeolite. The garnet is associated with yellow epidote, which seems to replace it in parts, and also with what is apparently diopside. The latter mineral occurs as prisms showing good cleavage, high refraction and birefringence, and an extinction angle of about 33° ; the mineral is positive. The scolecite occurs in the usual fibrous forms. It is sometimes quite clear, especially when it is adjacent to the garnet, but more often it is turbid ; it contains corroded grains of garnet, fibres of diopside, which also show signs of replacement, and epidote. Patches of heulandite are also present in the scolecite ; they contain grains of garnet and epidote and their junctions with the scolecite are highly irregular [78].

Grains of garnet have also been observed in a few other slides. In one of these [23] it occurs as minute crystals, six-sided in section, enclosed in clear scolecite or in chlorite ; in another slide there is a fairly well-defined band of greatly corroded grains lying between the rock and the overlying chlorite-scolecite zone [68] ; whilst in a

* *Mem. Geol. Surv.*, "The Neighbourhood of Edinburgh," 1910, p. 298.

third there is a small vesicle filled with chlorite, epidote, and clear albite with corroded grains of garnet enclosed in the albite and epidote [66].

A difficulty arises in the interpretation of these occurrences, for, as noted above, garnet is typically developed in the vesicles which have undergone metamorphism due to the intrusion of the granophyre. As will be shown later, however, the development of garnet in these circumstances is accompanied by other changes in the vesicles, none of which is shown in the slides described above. It may also be noted that the garnet in the Maol nan Damh slides always occurs practically at the walls of the amygdale, and shows obvious signs of corrosion and replacement. On the whole, the evidence points to the garnet and diopside being original vesicle-minerals, probably amongst the first to be deposited, which became unstable and experienced re-solution and replacement as the conditions changed and new minerals were deposited. FENNER records the similar occurrence of garnet in the Watchung basalt, where it also shows signs of corrosion and replacement by later-formed minerals.*

Thomsonite has not been detected in the vesicles on Maol nan Damh, but it occurs on the neighbouring hill of Coire Bheinn, which lies about two miles to the west. A section through one of the vesicles shows a thick layer of albite, which is only slightly turbid, succeeded by yellow epidote (in places), then prehnite, and finally thomsonite. The albite shows slight traces of corrosion against the epidote, but its boundaries with that mineral, though often rounded, are sharp and well defined. The epidote ends against the prehnite in a series of tufted aggregates and, when a plate of that mineral adjoins both albite and prehnite, the contrast between the two junctions is most marked. Albite shows corroded junctions with prehnite, which, in turn, has irregular outlines with thomsonite. The sequence is obviously (1) albite, (2) epidote, (3) prehnite, (4) thomsonite, and the earlier-formed minerals show signs of having been unstable towards the conditions under which the later ones were deposited.

III. *Sequence of Events in the Vesicles.*

In his summary of the characters of the occurrence under consideration, Mr CURRIE dwells upon the peculiar facies of lime-bearing minerals—a facies not recorded from any other locality in Scotland nor, as far as I am aware, from any locality hitherto described—and ascribes the origin of the vesicle-minerals to pneumatolytic action.† He did not examine the petrographical characters of the lava, but inferred from the minerals in the amygdales that it must have been originally a basalt containing a basic plagioclase, a pyroxene (either rhombic or monoclinic), and magnetite or olivine. Reasoning from the abundance of green earth, he also suggested the original presence of biotite.

It is clear from an examination of numerous sections that the rock is a typical, ophitic olivine basalt, now, of course, in an altered condition and, neglecting mean-

* C. N. FENNER, *loc. cit.*, p. 138.

† *Loc. cit.*, pp. 227–28.

while the exceptional cases, we may sum up the main features of the occurrence as follows :—

1. The rock is an olivine basalt with the purple augite typical of most of the lavas in Mull.

2. The felspars are albitised and veined with chlorite, and the olivine and augite also show alteration to that mineral.

3. The magma was rich in gases at the time of its eruption, and hence the vesicles are large and plentiful.

4. The cavities were sometimes the seat of igneous crystallisation subsequent to their formation, and, in the coarser portions of the rock, the vesicle-minerals have grown upon a pegmatitic layer of augite, albite, magnetite, and chlorite ; crystals from this layer are occasionally enclosed in the contents of the amygdales.

5. With the exceptions of chlorite and albite, the vesicle-minerals have lime for their principal base ; zeolites containing soda are exceedingly rare.

6. There is evidence of a more or less definite sequence in the deposition of the minerals, namely :—

(*a*) A layer of augite, albite, magnetite, and chlorite.
(*b*) Albite.
(*c*) Epidote.
(*d*) Prehnite.
(*e*) Scolecite.

Other sequences are :—

(*a*) Garnet.	(*a*) Garnet.	(*a*) Albite.
(*b*) Diopside.	(*b*) Albite.	(*b*) Epidote.
(*c*) Epidote.	(*c*) Epidote.	(*c*) Prehnite.
(*d*) Chlorite.		(*d*) Thomsonite.
(*e*) Scolecite.		
(*f*) Heulandite.		

7. Calcite is of rare occurrence, and hydrous oxides of iron and other typical oxidation products of weathering are almost entirely absent.

These facts suggest that the vesicle-minerals were deposited during the final period of cooling of the rocks, which seems to have been a long one. During the period of igneous crystallisation the normal pyrogenetic minerals, olivine, labradorite, and augite, were formed, the augite crystallising last. Consequently the magma, in the last stages of this phase, was rich in the augite-forming bases, and whilst the rock was solid, but necessarily at a high temperature, these formed the large, acicular augites occurring in some of the vesicles. When felspar occurs with them it is always albite in which inclusions are usually abundant. It forms turbid, lath-shaped crystals with much included chlorite, and also irregular patches much clearer and comparatively free from chlorite, but containing frequently grains and crystals of purple augite. It is difficult to determine whether the albite of the laths is primary or secondary in the sense that it is the albitised representative of a plagioclase originally more basic. There can be little doubt, however, that the clear compact patches were most probably deposited originally as albite, and, as they contain crystals of augite, no long period can have elapsed between the formation of the two minerals. The presence of this albite points to a transition from igneous crystallisation to a hydrothermal stage which would favour the formation of alkali-felspar * and also of the chlorite present in the pegmatitic layer.

During this hydrothermal stage the infilling of the vesicles was completed, the constituent minerals being derived partly from the residual material of the magma and partly from the breaking down of the igneous minerals which had already consolidated. In some of the chlorite and epidote we see the hydrothermal representatives of augite, a conclusion supported by the occasional occurrence, as noted above, of augite crystals in the cavities partly replaced by epidote, whilst the labradorite finds its counterpart in some of the albite, scolecite, and prehnite. It is evident, however, that whilst hydrothermal crystallisation of the residual magma accounts for the formation of a portion of the contents of the vesicles it probably does not account for them all. Some of the vesicles, especially the smaller ones, are packed with chlorite containing a kernel of epidote, or albite, or both; but the great majority contain a proportion of scolecite much larger than that of any other constituent. This fact can be accounted for by the albitisation of the felspars and the partial conversion of the augite of the rock to chlorite and hornblende, each of which changes liberates lime.

Albitisation is now known to be a fairly common occurrence in the igneous rocks of this country,† but the nature of the process seems to be imperfectly understood. In the cases cited by BAILEY and GRABHAM, it is a pneumatolytic phenomenon ascribed by them to the presence of carbon dioxide (or some other unknown constituent) in the original magma, which thus retained a large amount of soda in solution. The liquor then began to act on the felspars and albitised them. They also record the association with the albite of chlorite and epidote, the latter mineral representing some of the lime derived from the felspar; in most cases, however, the lime has been carried off in solution. DEWEY and FLETT also ascribe the albitisation of the felspar of the spilites to pneumatolytic action. ‡

At Maol nan Damh various considerations point to the albitisation having been a pneumatolytic change which took place during the cooling of the lava and marked the first step in the filling of the vesicles. This view gains support from the rarity of calcite and other oxidation products, which excludes the assumption that the change may be due to weathering; there is also the additional fact that rocks of

* *Cf.* F. W. CLARKE, *Data of Geochemistry*, 2nd edition, 1911, p. 348.

† *Cf.* E. B. BAILEY and G. W. GRABHAM, "Albitisation of Basic Plagioclase Felspars," *Geol. Mag.*, vol. vi, 1909, pp. 250–66; H. DEWEY and J. S. FLETT, "On Some British Pillow-Lavas," *ibid.*, vol. viii, 1911, p. 246.

‡ *Loc. cit.*, p. 204.

similar petrographical character are common amongst the plateau-basalts, and their felspars have not been albitised. It must, however, be conceded that albitisation is of universal occurrence in the rocks around the plutonic centre, although, in this area, it is only in the localities mentioned that the peculiar association of minerals in the vesicles has been detected. The cause and date of this general albitisation can be settled only by an examination of the rocks over the whole area, but the frequent association of the vesicle-minerals with those of igneous origin in the basalt of Maol nan Damh indicates that the change took place, in this case, during the last stages of cooling of the lava itself.

The albitised felspars almost invariably contain veins and patches of chlorite, which, as noted above, sometimes replaces entirely the original plagioclase. There does not seem to have been much introduction of soda, and the process was probably carried out by solutions containing chlorite and capable of dissolving the anorthite of the plagioclase. These solutions also partially chloritised the augite, and subsequently deposited their loads in the vesicles in the form of chlorite, prehnite, epidote, and scolecite, any surplus soda going to form albite, and, only very exceptionally, a zeolite containing soda. This rarity of soda-zeolites is an important point.

From the amount of secondary albite in the vesicles it is clear that soda was present in considerable quantity in the solutions, yet in nearly every case it has been deposited as albite—a fact which indicates strongly that the vesicle-minerals were deposited at a fairly high temperature.

DOELTER, in a suggestive paper,* has pointed out that, under laboratory conditions, a mixture of soda, alumina, silica, and water deposits analcite between temperatures of 190° and 420° C.; at lower temperatures natrolite is formed, and at higher temperatures either nepheline or albite. The formation of analcite seems to depend largely upon the temperature and to a very slight extent upon the relative proportions of the constituents, for it has been formed from solutions of very different compositions.† The conditions influencing the formation of albite are not so clearly understood, but, as shown by the work of BAUR,‡ and FRIEDEL and SARASIN,§ a temperature of 500° C. appears to be necessary.

As regards the sequence of events in the vesicles it is certain that their infilling was a continuous process, and the succession of minerals is what we would expect from deposition under conditions of falling temperature. Chlorite seems to have been deposited during all the stages, a fact remarked upon by FENNER || in his account of the Watchung basalt, but only very exceptionally does the vesicle-albite enclose it. It appears to have been formed in large quantities during, or slightly previous to, the deposition of epidote, which frequently encloses it and never shows sharp junctions

* C. DOELTER, *Tschermak's Min. Pet. Mittheil.*, 1906, vol. xxv, p. 97.

† *Loc. cit.*, p. 102.

‡ E. BAUR, *Zeits. f. physikal. Chimie*, 1903, vol. xlii, p. 570.

§ C. FRIEDEL and E. SARASIN, *Compt. rend.*, 1883, vol. xcvii, p. 290.

|| C. N. FENNER, *loc. cit.*, p. 174.

against it. Albite was in many cases the earliest vesicle-mineral, for it occurs in chlorite and epidote, against which it shows usually sharp, idiomorphic outlines. The succession, albite, epidote, prehnite, scolecite, is proved in many cases, and illustrates very well what happens during deposition under hydrothermal conditions. The albite was deposited first and is enclosed in places by the epidote which replaces it but slightly; with falling temperature prehnite is formed, which encloses and frequently corrodes and replaces the albite, a phenomenon also observed by FENNER,* who figures an example exactly similar to many of those seen in the present instance. Finally came the scolecite phase, during which the albite was also replaced, the epidote corroded, and even the prehnite attacked.

The survival of much of the pegmatitic augite raises a difficulty, for, although it exhibits signs of corrosion and occasional marginal alteration to hornblende and epidote, typically it is fresh and contrasts somewhat forcibly with the decomposed condition of a good deal of the augite of the rock. The explanation is probably due to the fact that when the solutions welled into the cavities they were saturated with chlorite and silicates of lime and soda, and therefore incapable of attacking the pyroxene. This is supported by the fact that in the subsequent phases albite is the mineral which shows in the highest degree the phenomenon of corrosion and replacement, the reason being that, after it had formed, it was constantly under the action of lime-bearing solutions which were able to decompose it.

The evidence that the vesicles were filled during the last stages of cooling may be stated shortly as follows:—

1. The vesicles sometimes contain pyrogenetic minerals.

2. The mineral association as far as the evidence goes is one demanding a temperature above the normal.

3. The silicates (with the exception of chlorite) were deposited in order of increasing hydration:—

(*a*) Albite . $Na_2O \,.\, Al_2O_3 \,.\, 6\,SiO_2$
(*b*) Epidote . $4CaO \,.\, 3Al_2O_3 \,.\, 6SiO_2 \,.\, H_2O$; $H_2O =$ 1·98 per cent.
(*c*) Prehnite . $2CaO \,.\, 3Al_2O_3 \,.\, 3SiO_2 \,.\, H_2O$; $H_2O =$ 4·4 per cent.
(*d*) Scolecite . $CaO \,.\, Al_2O_3 \,.\, 3SiO_2 \,.\, 3H_2O$; $H_2O =$ 13·8 per cent.

4. There is direct evidence that albite, epidote, and prehnite in the order named each passed through a phase of stability when they were deposited, and that they were more or less unstable to the succeeding phases.

5. Three periods, which grade into one another, can sometimes be recognised:—

(*a*) Period of magmatic consolidation.
(*b*) Period of pegmatitic crystallisation.
(*c*) Period of infilling of the vesicles.

The last-mentioned of the five points suggests analogies with the three phases

* *Loc. cit.*, p. 126.

described by BRÖGGER* in his account of the syenite-pegmatite veins of Norway, during the last of which the zeolites were deposited.

THE APPLICATION OF THE TERM "PROPYLITE."

It is clear from the descriptions of Professor JUDD already cited (*ante*, p. 2) that the vesicular basalt of Maol nan Damh, An Gearna, and Ben Fhada belongs to his group of *propylites*. The term, however, has been reserved by ROSENBUSCH † for a peculiar type of altered andesite, and was used by JUDD in that sense. The propylitic alteration is regarded by him as due to solfataric action connected with the presence of the acid intrusions, but quite distinct from the effects of contact metamorphism (*ante*, p. 2), to which cause Sir ARCHIBALD GEIKIE ascribed the peculiar condition of these rocks (*ante*, p. 2).

The lava of Maol nan Damh is a typical olivine basalt, and the evidence goes to show that its present characters and its peculiar vesicle-minerals arose during the formation of the rock itself. A propylite, according to ROSENBUSCH,‡ is an andesite altered by solfataric action, and it is clear that in this restricted sense the term cannot be applied to the basalt under discussion. But the pneumatolytic changes which it has undergone bear a strong resemblance to the alteration produced by the conversion of an andesite to a propylite, and, as basalts with these peculiar characters have a wide distribution in Mull, it might be advisable to extend the term *propylite* to them also.

It is natural to inquire into the cause of this peculiar condition of the basalts around the plutonic centres, a condition not observed so far in the plateau-ground; but the question can only be answered when the volcanic history of the district is made out. Meanwhile it is safe to say that the basalt of Maol nan Damh and some of the surrounding spurs must have been rich in vapours at the time of its eruption and was probably kept at a high temperature for a prolonged time. This suggests that the lava now occupies a site near the focus from which it was erupted.

THE METAMORPHISM OF THE VESICLE-MINERALS.

I. *Introduction.*

The subject of the metamorphism of the vesicle-minerals of lavas by intrusive masses of rock has been dealt with by Drs HARKER and MARR,§ who note that the minerals of the amygdales are the first to show the effects of metamorphism.||

* W. C. BRÖGGER, *loc. cit.*, pp. 160–81.

† H. ROSENBUSCH, *Mikroskopische Physiographie der Massigen Gesteine*, 4th edition, 1908, pp. 1102–05.

‡ *Loc cit.*, p. 1105.

§ A. HARKER and J. E. MARR, "The Shap Granite and the Associated Igneous and Metamorphic Rocks," *Quart. Journ. Geol. Soc.*, 1891, vol. xlvii, p. 292.

|| *Loc. cit.*, p. 296.

The changes induced in the surrounding andesites by the Cheviot granite have been described by Mr H. KYNASTON,* whilst Dr J. J. H. TEALL has described the metamorphic effects produced in the Arenig lavas by the Galloway granites.†

More closely related to the subject under consideration are the Tertiary basic lavas of Skye which, as described by Dr HARKER,‡ have been considerably altered by the large intrusions of granite and gabbro. He notes that the first minerals to be affected are the unstable contents of the vesicles, and records the interesting conversion of lime-soda zeolites to lime-soda felspars; epidote is also formed, and hornblende and biotite are developed at the expense of chlorite.

The metamorphosed amygdales of An Gearna and Beinn Fhada afford most instructive material for study because, on account of their large size, they usually contain portions of the material originally filling them, and it is only in close proximity to the granophyre that all traces of their original contents are obliterated. It is, therefore, possible to follow with confidence the course and nature of the metamorphism. How far the metamorphism induced in the lavas is due to the granophyre and how far to the minor intrusions so common in the district, it is impossible to say. It is, however, a fact that, despite local variations, the intensity of the changes increases as the margin of the granophyre is approached.

II. *The Petrography of the Metamorphosed Amygdales.*

It has been remarked already that one of the differences, obvious in hand-specimen, between the amygdales of An Gearna and those from Maol nan Damh consists in the somewhat paler appearance of the outermost layer of specimens from the former locality. Sections through this layer show that it varies considerably in character.

In some cases, especially when scolecite is abundant, it consists of long, bladed crystals of a pale green, pleochroic hornblende sometimes partially enclosed in large plates of albite full of inclusions. Associated with these are rod-like growths of black oxide of iron showing partial conversion to sphene. The hornblende shows good cleavage and frequently contains grains of magnetite and kernels of epidote. The albite encloses grains of epidote and crystals of hornblende. An occasional rounded mass of chlorite showing partial conversion to hornblende is also present. This layer is overlain by epidote, succeeded by scolecite, both of which enclose numerous fibres of hornblende. It is probable that the layer of hornblende and albite represents the pegmatitic zone of common occurrence in the vesicles of Maol nan Damh. The conversion of augite into hornblende liberates lime which has

* H. KYNASTON, "Note on Contact Metamorphism round the Cheviot Granite," *Trans. Ed. Geol. Soc.*, 1899, vol. viii, pp. 18–26.

† *Mem. Geol. Surv.*, "The Silurian Rocks of Scotland," 1899, p. 647.

‡ A. HARKER, *Mem. Geol. Surv.*, "The Tertiary Igneous Rocks of Skye," 1904, p. 50.

gone to form epidote and also to convert the chlorite to hornblende and the titaniferous oxide of iron to sphene [112].

In other amygdales, however, in which the chief contents are albite, prehnite, and epidote, the underlying layer consists of albite and augite which shows conversion to epidote and not to hornblende. Under the microscope the augite crystals are paler than those in the unaltered vesicles, and they contain kernels of epidote which, in some cases, replaces entirely the purple augite. A dull, turbid chloritic substance sometimes surrounds the augite crystals. It is not clear whether this change of augite to epidote is to be ascribed to metamorphism or to pneumatolysis during the original filling of the vesicle, since, as noted above, a partial conversion of augite to epidote has been observed in the unaltered vesicles [111].

Other instances occur in which the vesicle-minerals have been completely metamorphosed and the pegmatitic augite at the junction is practically unaltered, the only change being a slight marginal corrosion and alteration to hornblende. In such cases, however, the augite is enclosed by albite and was not originally in intimate association with an unstable zeolite which would give rise to steam with increase of temperature [26].

Some of the most interesting points connected with the metamorphism are shown by the zeolites, scolecite and thomsonite.

In the case of scolecite the first sign of alteration consists in the production of a slight turbidity, and the subsequent changes seem to depend to some extent on the minerals with which the zeolite was in intimate association. Alteration to epidote and prehnite is exceedingly common.

The secondary epidote occurs sometimes as a network of interlocking crystals with the spaces filled up with altered scolecite, and it can be distinguished in several ways from the primary epidote of the amygdales. Thus, it is usually colourless and shows no pleochroism, and it sometimes occurs as colourless rims surrounding a yellow kernel which often shows the original corroded outline and the inclusions of chlorite so typical of the primary epidote; the rim occasionally possesses a zonal arrangement parallel to the boundary of the core, and it shows weaker birefringence [15, 17].

The prehnite produced by metamorphism can be readily distinguished both by its appearance and mode of occurrence from the original prehnite of the vesicles. It forms confused aggregates of small crystals which ramify into the zeolite and sometimes replace it fibre by fibre [100, 50, 81]. The crystals are often large enough to permit of accurate determination under the microscope, but sometimes the fibres building the secondary aggregate replacing the zeolite are too small for that purpose, and, in such cases, the material was always crushed and the refractive index tested in a suitable oil. The secondary prehnite resembles in some respects the corroded rim which, as noted before, often separates the original prehnite from the scolecite; but it can be distinguished by its much greater abundance in the metamorphosed amygdales, by the manner in which it encloses dissected scraps of scolecite which are sometimes optically continuous, and by the fact that it not infrequently forms true pseudomorphs after that mineral.

A colourless pyroxene showing good cleavage and normal optical properties is a common mineral in the slides. It seems to have been formed around the inclusions of chlorite so common in the zeolite, for it is often dusted with turbid chloritic material. It occurs in fairly large crystals and plates and sometimes encloses scraps of scolecite [15]. It is identical in appearance to the pyroxene already described as a rare constituent of the vesicles on Maol nan Damh, but from its mode of occurrence in the present instance there can be no doubt that it is a product of metamorphism. Thus, when the epidote shows the core-and-rim structure already described, the pyroxene is frequently enclosed in the secondary epidote, especially near the junction with scolecite where the crystal often ends in a confused aggregate of the two minerals. Again, when the amygdale originally contained albite and scolecite in intimate association, the pyroxene has picked out and partially replaced the scolecite, whilst it never occurs in the albite. It sometimes occurs in prehnite [15, 16].

Garnet has also been formed at the expense of scolecite. It occurs either as idiomorphic dodecahedra, not infrequently showing pronounced zonal structure and optical anomalies, or as irregular patches traversing the zeolite. Inclusions are usually plentiful and consist of epidote, prehnite, and dull turbid fibres arranged in a subparallel manner towards the centre of the crystal [58]. Sometimes it forms true perimorphs consisting of a shell of garnet, pale brown in colour and with idiomorphic outlines, which encloses a spongy mass of secondary prehnite [43].

Thomsonite, though rare, affords an instructive example of the metamorphism of a zeolite containing both soda and lime. It has not been detected on Maol nan Damh, but, as previously mentioned, it occurs on Coire Bheinn, where the sequence is albite, epidote, prehnite, thomsonite, the various minerals showing the relationships already described. On An Gearna and Beinn Fhada the thomsonite shows conversion to prehnite and albite. In some of the slides the fibrous crystals of thomsonite are partially replaced by crystalline aggregates of finely fibrous secondary prehnite in intimate association with albite which forms irregular, turbid masses full of inclusions. To distinguish this secondary metamorphic albite from the original albite of the vesicle is a matter of some difficulty; but its absence of idiomorphism, its constant association with undoubted secondary prehnite, which it not infrequently encloses, and the occasional presence in it of fragments of thomsonite, all go to prove that it has been developed from the zeolite [50, 81]. Dr HARKER,* in his account of the metamorphosed amygdales of the Skye basalts, mentions that the lime-soda zeolites give rise to lime-soda felspars. So far, I have failed to detect in the vesicles felspars with a refractive index above that of balsam—a fact which is most probably due to the presence of steam in the vesicles during the metamorphism. Under such conditions

* A. HARKER, *loc. cit.*, p. 51.

basic plagioclases appear to be unstable, their representatives being albite and a lime-alumina silicate, such as prehnite, containing more or less combined water.

Hornblende is a common mineral in the metamorphosed amygdales, and has been formed by the alteration of the chlorite. It varies considerably in colour, being sometimes deep green and strongly pleochroic and sometimes very pale yellowish-green [9, 55, 59, 101]. It occurs in prehnite, epidote, and scolecite, and is always fibrous in habit. The change from chlorite to hornblende or biotite is quite a well-known effect of contact-metamorphism,* and, as lime is plentiful in the amygdales, and alkalies relatively scarce, hornblende has always been formed in preference to the mica.

These changes, which can be followed in detail in the less altered amygdales, become much more intense as the granophyre is approached. The solid primary prehnite, as well as the fibrous secondary material derived from the zeolites, is converted to garnet and epidote. The garnet varies considerably in appearance. It may be white to dark brown in colour and occurs either as idiomorphic crystals in the prehnite or as large irregular masses traversing and enclosing it. The mineral is frequently isotropic, but optical anomalies are also common; in some cases large rounded crystals consist of a brown, isotropic centre and a colourless, birefringent rim. Inclusions of epidote and prehnite are fairly common [26, 32].

The epidote is colourless, and crystals show pronounced zonal structure and remarkable variation in birefringence; occasionally sections show indigo-blue polarisation colours with positive optical sign, resembling in this respect zoisite rather than epidote. Inclusions of prehnite are sometimes present [25].

Sections through the amygdales collected from the screes lying nearest the granophyre margin on the north-east slope of Beinn Fhada show the most intense type of alteration noted. The zeolites have completely vanished, and their place is taken by a dull turbid substance which preserves their radiate structure. It is isotropic, and under high powers is seen to consist of minute yellowish grains of garnet. Any prehnite which has survived is studded with small hexagonal sections of garnet which is also replacing the epidote. The latter mineral occurs in crystals part of which consists of garnet, or it forms a corroded patch surrounded by garnet which sends off growths into the epidote [31, 40, 41].

Sphene is frequently present in the slides and forms grains and rounded crystals enclosed in the epidote or in the adjacent prehnite, whilst the chlorite has gone to hornblende, which sometimes forms compact green patches showing good cleavage and strong pleochroism [46].

III. *Summary and Conclusions.*

It is clear from a study of the metamorphosed amygdales that they were filled prior to the intrusion of the granophyre and that they participated in the meta-

* A. Harker, *loc. cit.*, p. 50.

morphic changes which it produced. These changes resulted in the production of the following minerals :—

Prehnite.	Garnet.
Epidote.	Sphene.
Pyroxene.	Albite.
Hornblende.	

With the exception of sphene, all of the above minerals occur as original constituents of the cavities, and the result of the metamorphism has been to recrystallise them in the reverse order to that in which they were originally deposited. Thus with the lime-bearing silicates the metamorphic changes progress as follows :—scolecite → prehnite → epidote → garnet, whilst the original order of deposition was :—garnet → epidote → prehnite → scolecite. Similarly with the lime-soda zeolites the order with rising temperature is :—thomsonite → albite and prehnite → epidote → garnet, whilst the original order of deposition was :—albite → epidote → prehnite → thomsonite.

The pyroxene and hornblende have been developed from the chlorite and scolecite or prehnite, whilst the sphene owes its origin to the titanium originally present in the augite and iron oxides of the rock, which found its way into the epidote (see analysis) and probably also into the chlorite of the vesicles.

The above evidence confirms in a striking way the view that the vesicles were originally filled under conditions of falling temperature, for, with the rising temperature occasioned by the intrusion of the granophyre, the only change has been to obliterate the minerals formed originally during the last and lowest temperature stages of the hydrothermal phase, and to form at their expense those minerals which crystallised in the first and highest temperature stages of that phase. Not only so, but the metamorphic minerals, considered from the point of view of their general distribution, have been developed in the reverse order to that in which their original representatives were laid down in the cavities.

An interesting point arises from the abundance of garnet in the metamorphosed amygdales and its rarity in the unaltered ones. This is probably to be ascribed to the great difference between the pressures under which the two sets of minerals were formed. Dr L. L. Fermor * has pointed out that garnet is a high-pressure mineral, and—as recrystallisation of the vesicle-minerals under the influence of the intrusion must have taken place at a considerable depth and, consequently, at a considerable pressure—the tendency would be for it to form at the expense of the other, less dense, lime-alumina silicates. In other words, the heat of the granophyre, combined with the high pressure, was steadily making the vesicles less hydrous and more favourable to the formation of garnet. Under the hydrothermal conditions, on the other hand, the temperature was falling, the pressure was never great, and the vesicles were becoming more hydrous and less favourable to the formation of garnet, or the preservation of any that might have crystallised. To judge from the vestigial appear-

* L. L. Fermor, *Records Geol. Surv. India*, 1913, vol. xliii, pt. 1, p. 42.

ance which the garnet presents in the vesicles where it does occur, it is quite possible that it may have been present more generally during the first phase of deposition and that it became obliterated during the succeeding stages.

ACKNOWLEDGMENTS.

I take this opportunity of expressing my best thanks to Dr J. S. FLETT and Mr E. B. BAILEY, B.A., of H.M. Geological Survey, for the interest which they have taken in the investigation and for the many valuable suggestions which they have made during the course of the work. To Dr ROBERT CAMPBELL, of the University, and Mr F. D. MILES, B.Sc., of the Heriot-Watt College, I am greatly indebted for help in the photographic part of the work. My gratitude is also due to the Carnegie Trust for defraying the cost of illustrating this paper.

EXPLANATION OF PLATES.

PLATE I.

Fig. 1. Ophitic Basalt [107] with Vesicles, magnified 27 diameters.—The light area to the right is a large vesicle containing prehnite and chlorite; at the bottom an acicular augite projects into the prehnite. The small vesicle to the left is filled with prehnite, enclosing a little chlorite; the dark crystals projecting into the prehnite are augite. Maol nan Damh, Ben More, Mull.

Fig. 2. Ophitic Basalt [70] with Vesicle, magnified 27 diameters.—To the right at the bottom is the rock, much decomposed, with numerous grains of magnetite. The large crystal projecting into the vesicle is purple augite pierced by laths of albite. To the left it shows a fracture filled with white scolecite, which occupies the rest of the cavity. The darker patches in the scolecite are chlorite. Just above the fracture in the augite is a crystal consisting of purple augite (dark) and pale yellow epidote (light). Maol nan Damh, Ben More, Mull.

Fig. 3. Ophitic Basalt [23] with Vesicle, magnified 12 diameters.—The rock, at the bottom, is succeeded by a pegmatitic layer consisting of lath-shaped crystals of purple augite (white), patches of chlorite (dark), and albite. At the junction with the rock the augites project radially to the wall, but towards the vesicle they lie tangentially. This layer is succeeded by a zone of chlorite and epidote, above which lies albite more or less turbid. Maol nan Damh, Ben More, Mull.

Fig. 4. Ophitic Basalt [110] with Pegmatitic Layer underlying Vesicle, magnified 27 diameters.—The layer on the right consists of lath-shaped crystals of augite, magnetite, chlorite, and albite. The clear, irregularly shaped patches are albite enclosing a few crystals of augite. Maol nan Damh, Ben More, Mull.

Fig. 5. Ophitic Basalt [111] with Vesicle, magnified 27 diameters. The rock, to the left, is a dense aggregate of augite, chlorite, and magnetite. The pegmatitic layer is well developed and consists of laths of augite, albite, magnetite, and chlorite. The white mineral in the vesicle is prehnite into which some of the underlying augite has wandered. Maol nan Damh, Ben More, Mull.

Fig. 6. Ophitic Basalt [111] with Vesicle, magnified 27 diameters.—The dark patch at the foot is the rock, which here consists of augite and chlorite. The turbid patches with black outlines which stretch on the left from the rock across the vesicle are albite which is being replaced and corroded by prehnite. Just above the middle patch of albite are two lath-shaped crystals of purple augite. The remaining clear and turbid areas consist of prehnite which, when it is turbid, has replaced albite. To the left of the central patch of albite there is a clear area consisting of prehnite surrounded by a turbid zone consisting of rectangular phantom crystals of albite replaced by prehnite optically continuous with the clear central portion. Maol nan Damh, Ben More, Mull.

Plate II.

Fig. 1. Ophitic Basalt [114] with Vesicle, magnified 27 diameters.—The dark area at the foot is the rock showing the outline of the vesicle. The light-coloured area filling up the hollows at the junction is a mixture of purple augite, magnetite, and prehnite. This is succeeded by a zone consisting of turbid albite, at the left towards the top; irregular patches of epidote, just above the centre; augite, in idiomorphic, lath-shaped crystals; and prehnite enclosing chlorite, which shows white in the photograph. A large augite crystal is seen at the top, on the left, projecting into albite; others, associated with magnetite, are seen on the right towards the top. Maol nan Damh, Ben More, Mull.

Fig. 2. Ophitic Basalt [109] with Vein, magnified 19 diameters.—The rock at the foot is succeeded by a layer consisting of large crystals of augite, one of which lies with its axis parallel to the wall of the vein, magnetite, albite, and chlorite. Above this is turbid albite which, at the top, towards the right, is succeeded by scolecite enclosing corroded scraps of epidote. Maol nan Damh, Ben More, Mull.

Fig. 3. Amygdale [113] in Ophitic Basalt, magnified 27 diameters.—The clear white material is scolecite. In the centre is a large, dissected crystal of epidote consisting of four fragments. The first is the irregular patch with tufted margins in the centre; the second is the rhomboidal piece lying directly beneath; the third lies immediately to the right of the second; and the fourth lies above the third. The four fragments have their cleavages parallel and extinguish simultaneously. The spaces between them are filled with scolecite enclosing rectangular turbid crystals of albite, in the centre and to the left connecting the third and fourth fragments of epidote. Near the foot on the left a turbid albite is in process of being replaced by scolecite. The dark areas at the left and right margins are epidote; beneath the latter one is a corroded albite. Maol nan Damh, Ben More, Mull.

Fig. 4. Ophitic Basalt [104] with Vesicles, magnified 27 diameters.—The small vesicle underneath is filled with analcite replaced by granular albite. The dark patches are chlorite moulded upon the analcite, and the long lath-shaped crystals which lie round the junction and also pierce the analcite are purple augite. A large one projects through the orifice connecting the small vesicle with the overlying main one. This vesicle is filled with a layer of augite, magnetite, and albite, seen on the right of the canal between the two vesicles; chlorite, forming the dark patch on the left; and albite, pseudomorphous after analcite, at the top. Maol nan Damh, Ben More, Mull.

Fig. 5. Ophitic Basalt [78] with Vesicle, magnified 27 diameters.—The dark area to the left is the rock. At the junction with the vesicle is a thin layer of garnet with little rounded and dissected masses isolated from the layer. Near the top is a projecting knob of garnet in process of dissection. Overlying the garnet is a mixture of scolecite and heulandite enclosing laths of diopside and epidote. The dark bar consists of diopside, showing signs of corrosion, and a dull birefringent material similar to that which surrounds much of the corroded garnet. The dark crystal on the right is a corroded piece of epidote. Maol nan Damh, Ben More, Mull.

Fig. 6. Metamorphosed Amygdale [17], magnified 27 diameters.—The amygdale is filled with scolecite showing incipient turbidity. Traversing the scolecite are crystals of epidote with yellow primary cores, enclosing chlorite and showing the original corroded outlines, and secondary, colourless rims. North-east slope of An Gearna, Ben More, Mull.

Plate III.

Fig. 1. Metamorphosed Amygdale [49], magnified 27 diameters.—The turbid patch on the extreme left and the two areas extending from the top and bottom respectively towards the centre are scolecite in process of replacement by prehnite, which forms the white areas in the photograph and, in the case of the upper and lower central masses of zeolite, forms little fibres traversing and replacing scolecite. The dark crystals to the left of the central zeolite are garnet, the one near the centre showing a core of secondary prehnite. The fibrous crystals, on the right towards the foot, are secondary epidote traversing secondary prehnite. Beinn Fhada, north end, east side, below the summit, Mull

Fig. 2. Metamorphosed Amygdale [58], magnified 27 diameters.—The turbid fibrous material, extending from the right towards the centre and forming the area at the bottom towards the left, is scolecite in process of replacement by prehnite, which forms the white areas. The mass of prehnite extending from the centre

to the top encloses remnants of turbid fibres of scolecite, the various portions of which are optically continuous. The dark inclusions at the centres of several of the prehnite areas are small garnets. The large crystal near the top towards the right is epidote; other crystals are seen at the margin on the right, and at the margin towards the bottom on the left. North-east slope of An Gearna, Ben More, Mull.

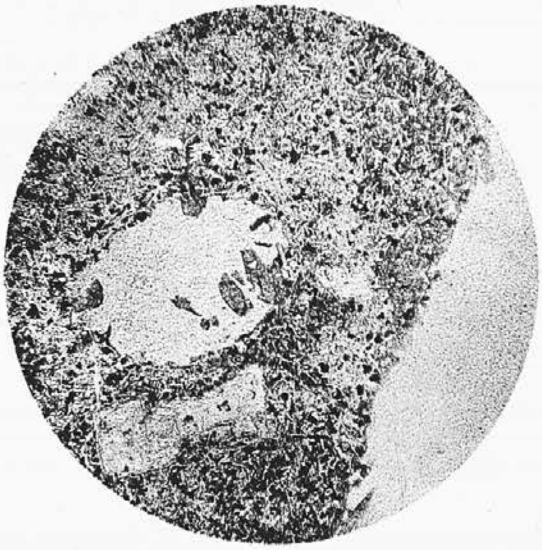
Fig. 3. Metamorphosed Amygdale [15], magnified 27 diameters.—The clear area to the right is primary prehnite enclosing diopside which is turbid and full of chloritic inclusions. The large crystals at the bottom and on the left are epidote, showing the core-and-rim structure. The turbid inclusions of diopside are confined to the colourless, secondary material of the rims. North-east slope of An Gearna, Ben More, Mull.

Fig. 4. Metamorphosed Amygdale [50], magnified 27 diameters.—The clear areas are prehnite, mostly secondary after thomsonite, whilst the turbid areas at the top and towards the right are secondary albite enclosing fragments of secondary prehnite and thomsonite. The corroded scrap in the prehnite at the centre is a zeolite, either scolecite or thomsonite. The crystals towards the bottom showing cleavage are epidote. Beinn Fhada, north end, east side, Mull.

Fig. 5. Metamorphosed Amygdale [41], magnified 27 diameters.—The turbid fibrous material is garnet secondary after a zeolite. The clear area at the top is also garnet enclosing and replacing prehnite. The colourless areas in the turbid material consist of garnet showing weak birefringence; it probably replaces epidote. Beinn Fhada, north-east slope, near the granophyre, Mull.

Fig. 6. Metamorphosed Amygdale [41], magnified 55 diameters, nicols crossed.—The large crystal crossing the field is epidote, secondary after prehnite some of which it occasionally encloses. The dark areas are garnet replacing prehnite and epidote. Beinn Fhada, north-east slope, near the granophyre, Mull.

W. F. P. M'LINTOCK: ON THE ZEOLITES, ETC., FROM TERTIARY LAVAS IN MULL.—PLATE I.



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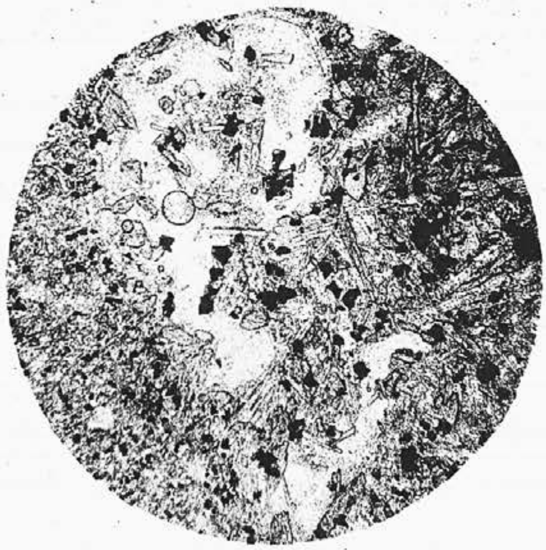

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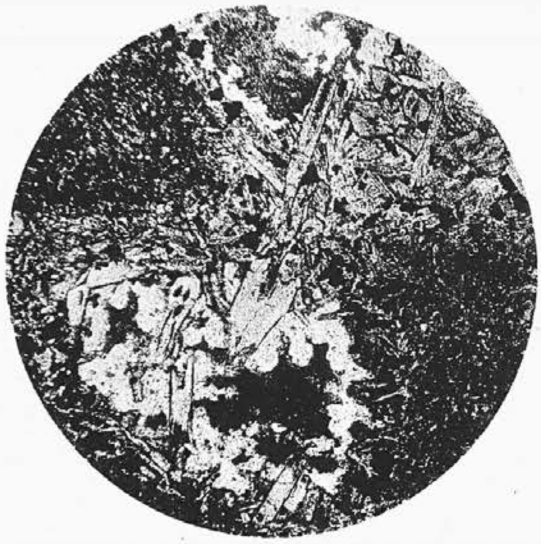
6.

W. F. P. M'Lintock, *photo.*

M'Farlane & Erskine, Lith., Edin.

W. F. P. M'Lintock: On the Zeolites, etc., from Tertiary Lavas in Mull.—Plate II.

1.



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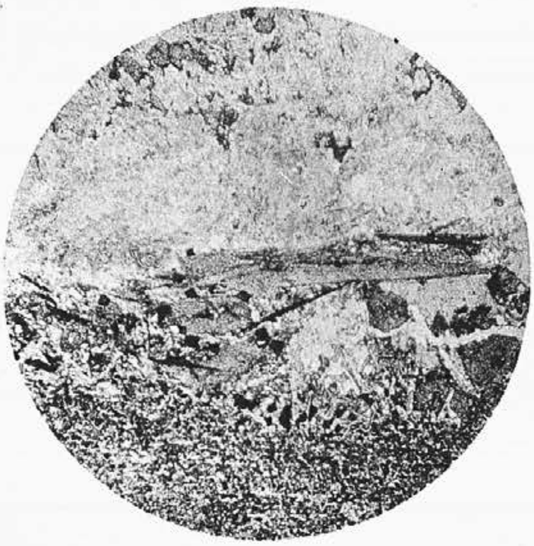

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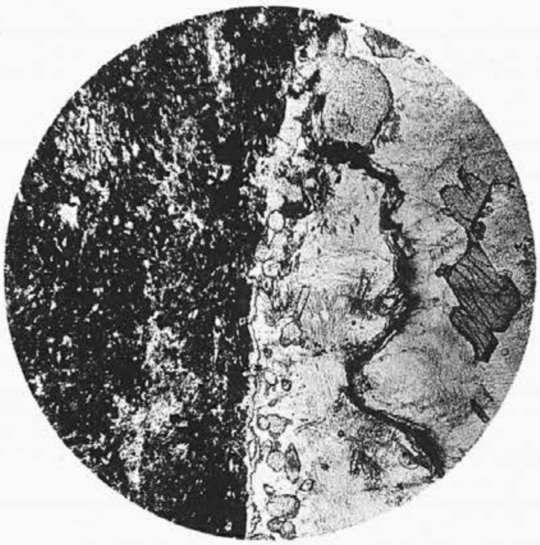

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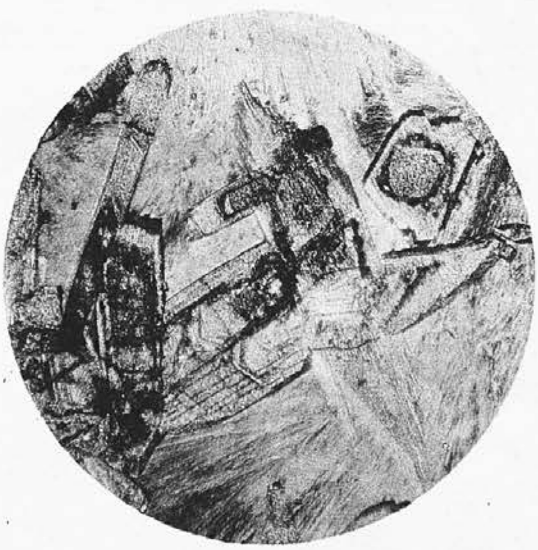

6.

W. F. P. M'Lintock, *photo.*

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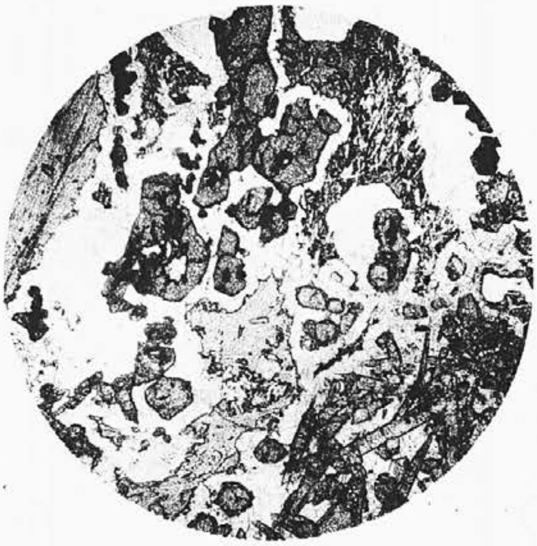
W. F. P. M'Lintock: On the Zeolites, Etc., from Tertiary Lavas in Mull.—Plate III.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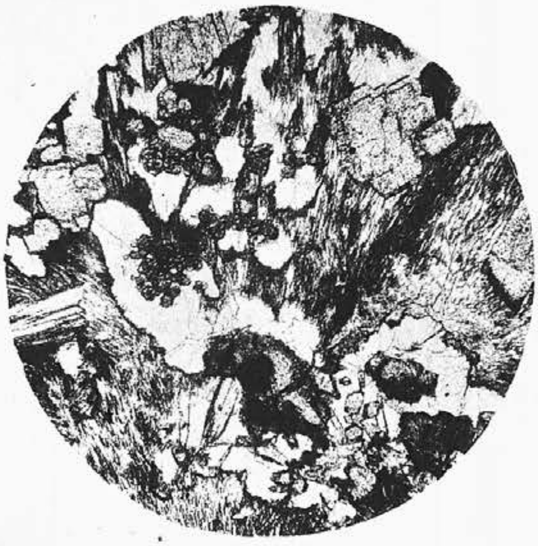
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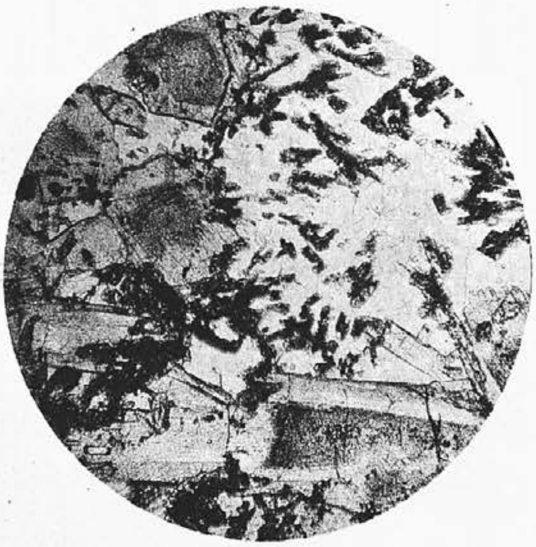
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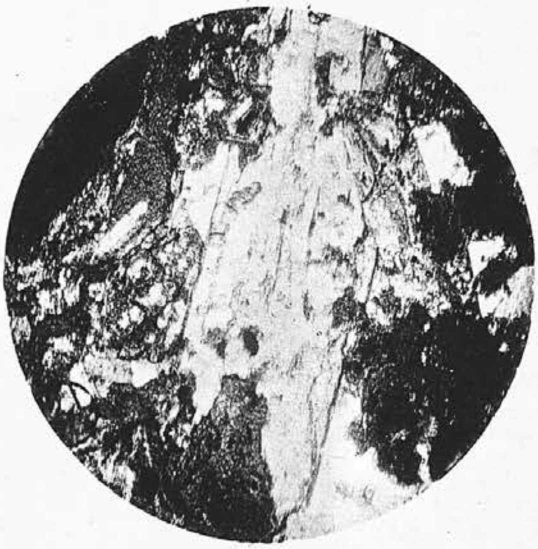
6.

W. F. P. M'Lintock, *photo.*

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1. *On the Zeolites and Associated Minerals from the Tertiary Lavas around Ben More, Mull.* By W. F. P. M'Lintock, B.Sc., Royal Scottish Museum, Edinburgh. *Communicated by* J. S. Flett, D.Sc., LL.D., F.R.S. (Plates I-III.) Price: to Public, 3*s.* 6*d.*; to Fellows, 2*s.* 9*d.*

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